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US Army Corps of Engineers
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Repair, Evaluation, Maintenance and Rehabilitation Research Program

Detection of Structural Damage on Miter Gates

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Prepared for Headquarters, U.S. Army Corps of Engineers

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	Problem Area		Problem Area
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HY	Hydraulics	OM	Operations Management
CO	Coastal		

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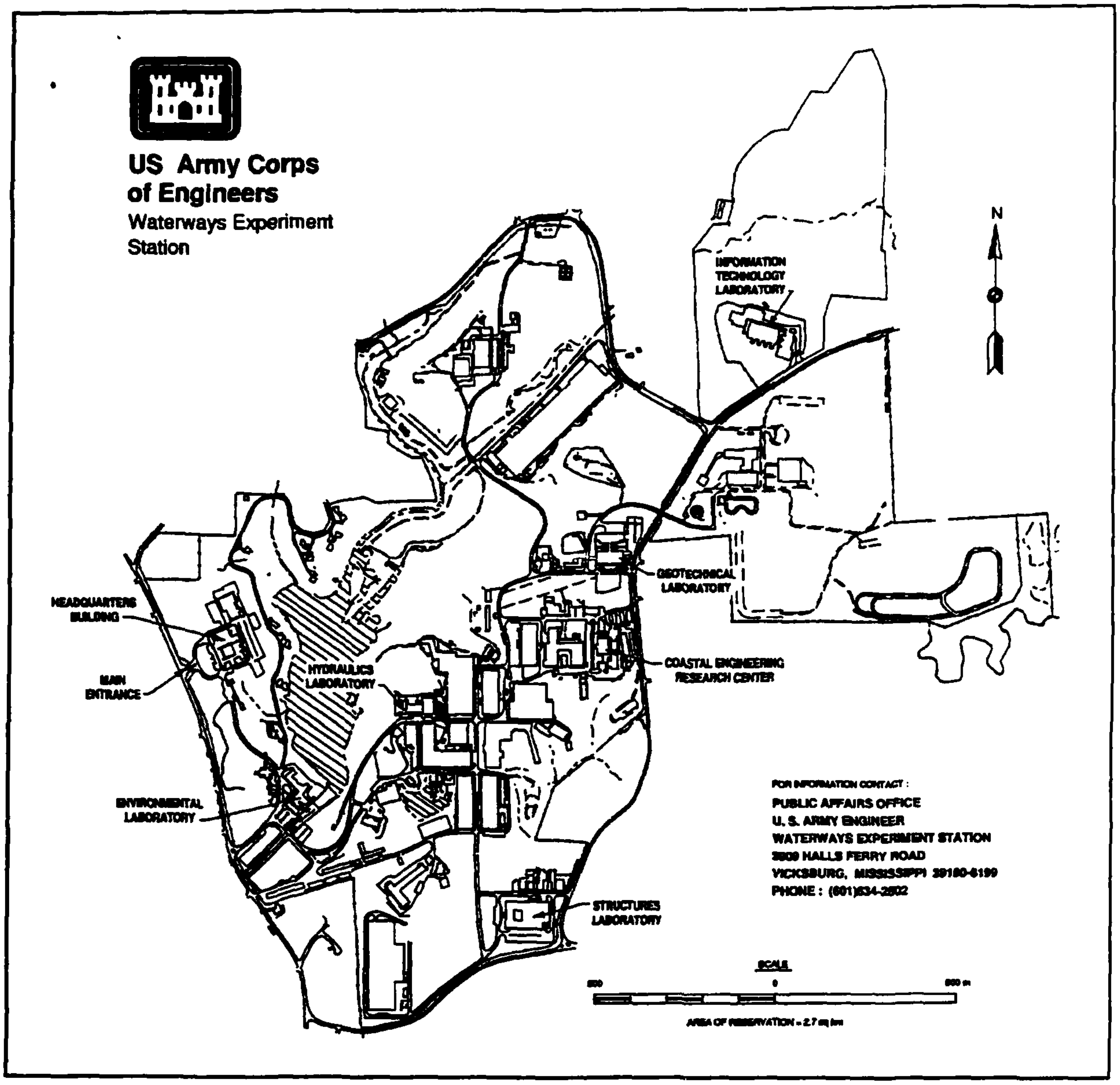

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Preface

The work described in this report was sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Concrete and Steel Structures Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The work was performed under the REMR Work Unit 32641 "Evaluation and Repair of Hydraulic Steel Structures (HSS)," for which Mr. Joseph A. Padula, Information Technology Laboratory (ITL), U.S. Army Engineer Waterways Experiment Station (WES), is Principal Investigator. Experimental studies described in Chapter 2 of this report were performed under the Computer-Aided, Structural Engineering (CASE) Project. The CASE Project is funded by HQUSACE, Civil Works Directorate, and is managed by the Scientific and Engineering Applications Center (S&EAC) of the Computer-Aided Engineering Division (CAED), ITL. Mr. Don Dressler, HQUSACE, is the REMR Technical Monitor.

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The work was performed by Bridge Diagnostics Incorporated (BDI) under U.S. Army Corps of Engineers (USACE) Contract No. DACW39-91-C-0102. The report was prepared by Mr. Brett C. Commander, BDI; Mr. Jeff X. Schulz, BDI; Dr. George G. Goble, BDI; and Mr. Cameron P. Chasten, formerly of ITL, WES, under the general supervision of Mr. H. Wayne Jones, Chief, S&EAC, and Dr. N. Radhakrishnan, Director, ITL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
inches	0.0254	meters
kip-foot	1355.818	newton-meter
kips (force) per square inch (ksi)	6894.757	kilopascals

1 Introduction

Background

Approximately 40 percent of the locks on the U.S. inland and intracoastal waterway systems are over 50 years old, and the median age of all lock chambers is approximately 35 years (Headquarters, U.S. Army Corps of Engineers (HQUSACE) 1988). Many of the hydraulic steel structures (HSS) (primarily lock and dam gates) are nearing their design life in age and require assessment for needed rehabilitation. To acquire data for assessment purposes, experimental systems can measure the actual response of HSS subjected to various loading. However, with most systems, only a few selected points on a structure can be monitored. An optimum evaluation system would integrate both analytical and experimental techniques. An analytical model of such a system can be systematically modified until it simulates structural behavior observed under experimental conditions. This type of integrated evaluation system is currently under development (Commander et al. 1992a).

A primary goal of this project is to develop structural evaluation tools that can be used to assess the current condition of aging steel lock gates. In recent studies, it has been demonstrated for miter (Commander et al. 1992b, 1992c, 1993) and vertical lift lock gates (Commander et al. 1994) that field testing can be done efficiently and that measured structural response can be represented realistically with a simple finite element model. (In some cases, systematic modification of ambiguous model parameters such as boundary conditions is required to achieve an acceptable model.) An obvious extension of this work is to study how this integrated system can be used to identify existing structural deficiencies on the basis of measured data without detailed structural inspections. The focus of this study is to use the data and knowledge acquired during the previously mentioned studies to determine if and how the integrated (experimental and analytical) evaluation system can be automated to assist an engineer in identifying structural damage or deficiencies.

Five field tests were performed on lock gates (Commander et al. 1992b, 1992c, 1993, and 1994), and the data of four different lock gates indicated some form of unexpected behavior. In each case, the unexpected

behavior could be determined subjectively by the analyst through careful evaluation of the experimental field results and comparisons with the analytical data. The goal of this study is to determine if a more objective or automated procedure can be developed to supplement this subjective approach that is based on engineering experience. This report discusses initial developments of an automated procedure and attempts to employ a systematic approach to identify simulated damage for two miter gates (for this study, the damage was simulated so that conditions were known precisely).

The following section outlines some objectives of this study and some additional considerations. Chapter 2 describes results of the four cases in which lock gates were tested, analyzed, and determined to exhibit unexpected structural behavior. These cases provide some background information and experience required for development of systematic procedures in this study. Chapter 3 discusses systematic procedures used to evaluate a damaged structure. Finally, advantages and the limitations of using the integrated evaluation system to determine damage conditions are presented in Chapter 4.

Objectives and Considerations

The primary objectives of this study were (a) to determine if the integrated (experimental and analytical) evaluation system could be automated to identify and locate existing deficiencies using some systematic approach (or automated procedure) and (b) to explore development of such a systematic approach. In determining a systematic approach to identification of an existing structural deficiency, several items had to be considered:

a. Define "deficiency" as it pertains to this study. For this study, a deficiency is a condition that causes any irregular or unanticipated structural behavior.

(1) Unexpected boundary conditions that vary with load levels, as occurred in two field tests (Commander et al. 1992c, 1993), may or may not constitute a deficiency.

(2) Deviation of measured and analytical behavior at various load levels may or may not indicate a deficiency.

b. Determine how to consider redundancy. If certain members of a structure do not support their intended load, but structural redundancy still allows safe operation, a structure might not be considered deficient.

c. Identify events that are most likely to cause a structural deficiency. Barge impact, construction tolerance, loss of section due to deterioration or cracking, and fracture due to fatigue are possible causes.

d. Identify locations on a structure most likely to be deficient. These locations should be examined more closely during testing and analysis.

e. Consider the various levels of computer system use or capability (this would require different levels of corresponding system requirements).

(1) Consider the capability of the system to indicate that there is some sort of abnormal behavior. Given a positive indication, perform an inspection on the entire structure.

(2) Consider the capability of the system to locate a deficient area.

(3) If a structure is deficient in several locations, investigate the likelihood of identifying all deficient locations and the effects this would have on the automated procedure.

(4) Consider the capability of the system to locate and quantify (identify cracking, corrosion, etc.) the affected area.

Once these items were considered, specific procedures for determining if deficiencies were present needed to be developed. The basis for identifying deficiencies were the comparison of experimental and analytical responses. Comparisons can be based on the correlation of experimental and analytical data that are expressed as a function of an independent variable (i.e. strain or flexural curvature as a function of load level).

With the above considerations, the task of developing a system that has the ability to locate damage (or deficiency) is not an easy process. A systematic approach is necessary in order to address these considerations. Since some type of deficiency or unexpected behavior was evident on four out of five lock gates previously tested, study of these results provides some insight to the problem. With the lessons learned from four case studies (discussed in Chapter 2), it is possible to address most of the above considerations.

2 Case Studies of Damage Detection and Assessment

Field tests were recently performed on several different lock gates (Commander et al. 1992b, 1992c, 1993, and 1994) including vertically and horizontally framed miter gates and vertical lift gates. Each test consisted of monitoring strain at over 30 locations on the structure as head differential and operating loads were applied. Analytical models were developed, analyses were conducted to obtain computed response data, and measured and computed data were compared for each case. In several instances, some type of damage or unusual behavior was detected by examining measured strain data at the time of the testing. The unusual behavior could generally be explained through the examination of the measured strain data and subsequent comparisons with computed strain data. In addition, the mechanism causing the damage or unusual behavior was identified, and/or the resulting effect on the structural performance was determined. Although the reasons for unusual behavior could be resolved in most cases, a trial and error type approach that involved subjective input by the analyst was required.

The following sections describe case studies that provide examples for which deficiencies or unusual behavior were detected and/or explained using the combination of experimental and analytical results. These cases provide the foundation for this study and illustrate the value of the testing and analysis correlation regarding structural assessment.

Emsworth Lock and Dam Miter Gate

Field testing and analytical studies were conducted for a relatively new miter gate leaf at the Emsworth Lock and Dam on the Ohio River (Commander et al. 1992c). The test was performed on a single leaf of the downstream lock gate. This study illustrates how the occurrence of unexpected field data can be used to identify structural deficiencies or unanticipated behavior and that effects resulting from damaged members can be assessed through comparison of analytical and measured strain data.

Strain data were recorded at 32 locations for two loading conditions: (a) varying head differential and (b) gate operation. At very low levels of head differential, relatively large strains were measured at several locations during the head differential test. At these locations, the strain data varied as a function of head differential in a highly nonlinear manner (this response is expected to be near-linear). After the head differential tests were completed, the gate operation tests were performed (gate was opened and closed). During the operation tests, zero strain was recorded at one of the diagonal members. This was unusual since significant torsional forces are applied to the leaves as they swing through the water and the diagonal members provide most of the torsional resistance; relatively large strains occur in diagonal members during operation. Inspection of the diagonal revealed that it was completely loose and was void of any pretension. Although this structure is operated several times per day, this was not known prior to the test.

Examination of the field data and subsequent comparisons with analytical data revealed some effects of the loose diagonal. The large strains measured during the initial stage of the head differential test occurred at locations near the diagonal member connections (downstream flanges of the top girder, vertical girder, quoin girder, and miter girder). The fact that unusually large strains occurred near the diagonal connections indicates that some type of torsional deformation of the gate leaf was occurring as head differential increased. It was also apparent from the strain records that the torsional deformation occurred only under low loads (the first few feet of head differential). The rate of variation in strain as a function of head differential was very high for low levels of loading and became consistent with that predicted by the analysis for higher levels.

From these observations, it was concluded that the leaf had warped such that the bottom girder was not fully in contact with the bottom sill due to the loss of diagonal pretension. The occurrence of large strains at low head differential was due to the torsional deformation (or straightening) as the increasing head differential load pushed the bottom girder back against the sill. The bottom girder apparently came into contact with the sill along its length at a load of approximately 2 to 4 ft[1] of head differential. Once the bottom girder was against the sill, no further warping occurred, and the measured strain records were consistent with the analytical results.

[1] A table of factors for converting non-SI units of measurement to SI units is presented on page vii.

Mississippi River Locks No. 27 Lift Gate

The upstream leaf of a vertical lift gate at Mississippi River Locks No. 27 was tested and analyzed (Commander et al. 1994). The purpose of this test was to measure strain levels and determine general response characteristics of the lift gate while subject to normal service loads. Results from this study were to aid in the design of a new lift gate. Field data and analysis results were both utilized to determine important aspects of the loading and response behavior. Through analysis of field data, a structural deficiency was identified, and unknown boundary conditions and loading were assessed through comparison of analytical and measured strain data.

During the field test, strains were recorded at approximately 60 different locations as the leaf was lifted to apply vertical load and as the lock chamber was emptied and filled to vary the head differential. Data obtained from the head differential test indicated that a net pressure was applied to the gate leaf in the downstream direction, which indicates that the seal between the gate leaf and the upstream sill was inoperative. (It was later determined that the seal had been removed several years prior.) With no seal, the hydrostatic pressure distribution on the gate leaf is significantly different from that of a leaf with a seal. Analytical models were used to determine the associated loading conditions.

Strain data of the vertical load tests showed that the gate was resting on the bottom sill, and boundary conditions for the analysis model were defined accordingly. Comparison of the computed and measured strains indicated that the bottom girder was not fixed, but some amount of resistance was provided by friction along the bottom sill. In the analytical model, the horizontal resistance along the bottom sill was approximated with a series of linear elastic springs. The stiffness of the springs could not be estimated by any standard means. Therefore, the spring stiffness was determined through an iterative process in which the stiffness was varied until analytical results compared reasonably with the strain measurements. A parameter optimization procedure (Commander et al. 1992a) was used to determine spring stiffness and resulted in a significantly improved correlation between the computed and measured strains. The data showed that the bottom sill was providing horizontal resistance to the gate leaf, and an approximate linear value of the resistance was obtained.

Mississippi River Locks and Dam No. 26 Lift Gate

The ability to assess structural damage was further demonstrated through experimental and analytical studies of a vertical lift gate at the Mississippi River Locks and Dam No. 26 (Commander et al. 1994). In this study, a contributing cause of a known deficiency (crack) was determined through evaluation of analytical and experimental data.

During a visual inspection prior to one of the field tests, a crack was identified at a welded connection between a diaphragm flange and a girder flange. The structure was instrumented in the vicinity of the crack, and testing was conducted to obtain data so that the cause and effect of the crack could be investigated. The analytical data and the measured strain on the diaphragm flange plate indicated that under vertical loading, significant tensile stresses developed in the diaphragm flange at the crack location. The high tensile stresses were caused by excessive shear deformation of the gate leaf due to vertical loading. Damage of this type would not likely be detected through testing procedures alone, unless strain transducers were placed next to the crack. Visual inspection would likely be required to detect this type of damage. However, it is important that the cause of the cracking be determined so the situation can be prevented in the future and critical areas for inspection can be determined.

The results of this study demonstrated that (a) structural components can experience damage from secondary effects that are not likely considered during the design (i.e., shear deformation of elements not intended to provide shear strength), and (b) the combination of field testing and analysis can provide considerable insight into the cause and effect of known damage. This information is important for future designs and for defining critical areas for inspection.

Red River Lock and Dam No. 1

Another case study relevant to damage assessment is the Red River Lock and Dam No. 1 field test and analysis (Commander et al. 1993). Testing was performed to obtain structural response data for a horizontally framed miter gate. Strain measurements were recorded while the miter gate was subject to head differential and operating (opening and closing) loads. Although no structural deficiencies were observed, correlation studies for the experimental and analytical data indicated that irregular boundary conditions were present at low levels of head differential.

At the time the test was performed, there was very little head differential between the upper and lower pools. The head differential was about 13 ft, which is quite small compared with the maximum design head differential of 36 ft. Strains were measured at 32 locations on the structure, all of which were above the lower pool elevation. The upper six horizontal girders and the upper portions of the vertical diaphragms were instrumented. Strain transducers were located symmetrically about the center of the leaf with three of the girders being instrumented along their lengths at approximately their quarter points.

The measured strains at symmetric locations about the leaf center line on the horizontal girders were not equal. Since the transducer locations, the structural geometry of the gate leaf, and the hydrostatic loading were all symmetric about the leaf center line, the strain responses at symmetric

locations should have been equal. However, flexural bending responses measured near the miter end of the girders were in some cases opposite in direction (negative moment versus positive moment) to those measured near the quoin ends.

Transducers at the miter and quoin ends of the girders were located near the inflection points of the girders. Therefore, the bending response would change from positive to negative within a short distance, and slightly inaccurate placement of the transducers could result in data that indicated abnormal flexural behavior. However, the strains at the miter end were near zero for low head differential, and, as the head differential increased, the flexural response measured at the miter ends began change towards the expected condition. Since the head differential was so low, the load cycle was complete shortly after the response change began to occur.

The behavior measured at the miter ends of the girders indicated that a change in boundary conditions occurred with increasing head differential. It was speculated that some of the girders were not fully mitered with their respective counterparts prior to the application of the hydrostatic load. This would result in small gaps between the miter ends of the girders for low head differential loads. The changes in boundary conditions would then occur as the head differential load increased enough to force the miter ends of the girders together.

In testing this hypothesis, analyses were conducted with models having no boundary conditions at the miter ends of the top five girders. Correlations of the modified model analysis results with the measured strains showed a marked improvement compared with the original results. Similar to the measured results, the model showed unequal strain responses at the miter and quoin ends of the horizontal girders for low levels of head differential. This indicated that the hypothesis of initial gaps at the miter ends of various girders was at least partially correct.

The only reason that the effect of the gaps between the horizontal girder contact points was notable was that the applied load was so low. The effects of the gaps were apparent through the majority of the loading measured. The presence of the small gaps is relatively insignificant from a structural point of view since they close as the load increases. At the low level of loading considered, initial gaps are likely to exist for any miter gate simply due to fabrication and construction tolerances and is not considered to be a concern. However, the measured behavior proved to be important for this study, because unexpected strain histories were measured and the cause was identified by simulating the deficiency analytically.

Case Study Conclusions

Of the five lock gates that were tested, four exhibited some type of unexpected structural behavior. In two instances, conclusions regarding structural response were determined directly by examining strain measurements. As a result of the Emsworth miter gate test, a slack diagonal was found, and the Locks No. 27 lift gate test results indicated that a seal was not effective. It was also verified that the combination of experimental and computed results could be used to provide additional information to further assess irregular structural behavior. For the Emsworth miter gate, the effect that the loose diagonal had on the rest of structure was determined. Unknown loading and boundary conditions due to friction along the bottom sill were approximated for the Locks No. 27 lift gate. Also, important information for design and inspection was obtained from the Locks and Dam No. 26 lift gate test results by determining the cause of cracking in a diaphragm flange plate.

Although the results from the testing and analysis exercises provide a strong background for this study, several items need to be addressed before developing any systematic procedures for locating and assessing deficiencies. Since the primary goal of the field testing was to verify the feasibility of the integrated approach to structural evaluation, only the overall behavior of each structure was investigated. This entailed instrumenting only the primary members of the structure at 32 locations and comparing the results to a finite element model with a relatively coarse mesh. As this study progressed, it became apparent that information from only primary members at 32 locations may not be sufficient to locate and quantify structural deficiencies.

Additionally, for all three miter gates that were tested, only one leaf was instrumented since it was assumed that miter gate leaves behave symmetrically about the center of the lock chamber while in the mitered position. If one leaf is damaged significantly, the behavior will likely not be symmetric. Therefore, for this study the assumption of symmetric behavior is a limitation. These and other considerations are discussed in detail in the following section.

3 Simulated Deficiencies - Detection and Assessment

For this study, a deficiency is a condition that causes any irregular or unanticipated structural behavior. Unanticipated behavior is that which is not accounted for in design and can change the load resistance capabilities of the structure. The loose diagonal on the Emsworth Locks and Dam miter gate would be considered a deficiency since it resulted in irregular nonlinear behavior, even though the structure still performed under load. With the above definition, a deficiency also existed in the boundary conditions of the Red River miter gate when the leaf was not loaded. Under no head differential, a slight gap existed between the miter contact points of the girders and caused an unexpected bilinear strain response to occur. When the girder ends came into contact as the structure was loaded, it responded as assumed for design. Although the overall safety and integrity of the structure was not impaired, it behaved differently than assumed in its design.

In these two examples, strain response as a function of loading was highly nonlinear, and a near-linear response would occur for a perfect miter gate. Therefore, a deficiency might be indicated by a highly nonlinear response (where a near-linear response is expected) or a response that deviates significantly from the expected behavior. Because lock gates are highly indeterminate structures, the load transferred to a structural member may not be linearly related to the applied load.

A primary goal of this study is to investigate techniques that may be used to determine whether or not a deficiency exists (without prior knowledge of a deficiency). One way to identify deficiencies is to perform structural inspections visually while focusing on critical areas (considering primary causes for deficiencies). This type of inspection program can be based only on past experience with a particular type of structure. Although visual inspection can reveal obvious deficiencies or damage, it is not effective for quantifying behavior of a structure, and submerged portions of a structure cannot be inspected without divers.

A realistic alternative to identify the presence of a deficiency is to use the integrated experimental and analytical approach. Field tests can be conducted to measure structural response, and analytical models can be used to calculate the response. Deficiencies that otherwise would not be noticed may be detected by examining the measured data and comparing the data to analytical results. The presence of a deficiency having been established, its extent and effect should be quantified. One alternative is to perform a detailed inspection focusing on critical areas which can generally be identified based on the measured behavior. Another alternative is to calibrate or modify the analytical model until its response matches that measured in the field. A good correlation between the experimental and computed data indicates that the load model, boundary conditions, and structural geometry are all represented accurately. A great deal of information concerning the structural behavior and potential deficiencies can be gained through the process of model calibration. When an acceptable correlation is obtained, the analytical model represents the actual structure, and the modifications required to obtain the best correlation are generally indicative of significant deficiencies. Even in cases where it is not possible to accurately represent the structural behavior analytically, the irregular structural behavior due to the deficiency can at least be identified.

In the case studies discussed in Chapter 2, examination of measured strain data proved extremely useful in finding deficiencies, and in several cases the comparison of measured and computed strains led to the location and quantification of the deficiency. A parameter optimization process was used in quantifying deficiencies, as illustrated by the evaluation of unexpected resistances along the bottom sill of the Locks No. 27 lift gate. The parameter optimization is an automated iteration process in which ambiguous parameters are varied to minimize the difference between measured and computed data (Commander et al. 1992a). The Locks No. 27 lift gate case study provides an example of the process of identifying and quantifying a deficiency. Measured strains on the lower girders were significantly less than predicted by use of the analytical model because assumptions regarding horizontal resistance between the gate and the bottom sill were not initially considered. With the previous definition, this behavior is due to a deficiency since it was not accounted for in design. The deficiency could be quantified by modifying the model to account for this resistance. It was found that significant horizontal resistance existed along the sill. It would be nearly impossible to detect this type of behavior through visual inspection. For each of the field tests, damage assessment was performed through a subjective and intuitive process of comparing measured and computed strain data.

A primary goal of this study is to determine if damage assessment can be performed by a more automated procedure. The parameter optimization process has proven to be useful in quantifying known deficiencies. Therefore, by optimizing various structural parameters throughout the structure, it may be possible to detect, locate, and quantify unknown deficiencies (i.e., damage assessment). If the response of a damaged structure can be simulated by altering various structural parameters in the analysis,

then the changes in parameters represent the damage or its effect. This process is limited by the assumption that the original analysis model accurately represents the structure without damage. With the exception of the deficiency (i.e., damage), the applied loads, boundary conditions, and structural geometry defined for the model must be truly representative of the actual structure.

Damage Assessment Process: Development and Verification

In order to develop and verify a damage assessment process, it is beneficial to compare the behavior of an undamaged structure with that of the same (or similar) structure with damage. The deficiency or damage should be well defined and significant enough that its effect can be easily identified. With a well-defined base condition, it is easier to verify the assessment process. To investigate the feasibility of automated damage assessment, data from a damaged structure are required. Since structures with well-defined deficiencies are not available and inducing structural damage to an existing structure is not acceptable, data for this study were obtained by simulating damage with analytical models of miter gates. Damage on primary members was simulated analytically for two miter gates. Results from the models in which damage is simulated (hereafter referred to as the simulated damage model) are considered to be measured results in this study.

Analyses were performed for damaged and undamaged conditions. Results from analysis of the undamaged models were compared with those of the simulated damage models (analogous to comparing analytical data with measured data) to determine the effect of the damage on the structural behavior. Attempts were made to identify the simulated damage through parameter optimization of the undamaged model. The following sections outline the details of data comparison, how the damage was simulated, and how the optimization process was implemented to evaluate the damage. Based on the findings, various conclusions are drawn concerning the applicability and limitations of the optimization process.

Data comparison

In this study, comparisons of the simulated measured data and analytical data are performed for head differential hydrostatic loading. The data consist of strain at specified locations (gage locations) as a function of head differential. The number of strain values used in the data comparison is based on the number of gage locations and the number of different load cases. The load cases are defined by 2-ft incremental changes in head differential.

Data are compared visually on graphs of measured (simulated damage model results) and analytical strain versus head differential level and by various numerical comparison quantities. Numerical comparison quantities include absolute error, average gage error, percent error, and correlation factor. The absolute error E_{abs} is the summation of the absolute values of the strain differences (difference in measured and calculated strain for a given location) for each location and load case considered. The average gage error E_{ave} is simply E_{abs} divided by the number of locations and load cases. The percentage error E_{per} is calculated by dividing the summation of the strain differences squared by the summation of the measured strains squared. The correlation factor CF is a measure of how strongly two variables are linearly related or how closely the shape of the measured and analytical response curves match. The error functions can be computed for individual gage locations as well. This allows determinations to be made as to which locations on the structure produce good agreements between the computed and measured results and which locations do not. The error quantities are calculated by use of the following equations.

$$E_{abs} = \sum_{i=1}^{n} | \varepsilon_{f_i} - \varepsilon_{c_i} | \tag{1}$$

$$E_{ave} = \frac{E_{abs}}{n} \tag{2}$$

$$E_{per} = \frac{\sum_{i=1}^{n} (\varepsilon_{f_i} - \varepsilon_{c_i})^2}{\sum_{i=1}^{n} \varepsilon_{f_i}^2} \times 100 \tag{3}$$

$$CF = \frac{\frac{1}{n} \sum_{i=1}^{n} (\varepsilon_{fi} - \bar{\varepsilon}_f)(\varepsilon_{ci} - \bar{\varepsilon}_c)}{\sigma_{\varepsilon f}\, \sigma_{\varepsilon c}} \tag{4}$$

where

ε_{fi} = measured strain at a given location for a given head differential load

ε_{ci} = computed strain corresponding to ε_{fi}

n = number of gage locations times number of applied load cases (total number of different strain readings)

$\bar{\varepsilon}_f =$ mean value of measured strains

$\bar{\varepsilon}_c =$ mean value of computed strains

$\sigma_{\varepsilon f} =$ sample standard deviation of measured strains

$\sigma_{\varepsilon c} =$ sample standard deviation of computed strains

Simulated damage and optimization

Various degrees of damage were simulated using analytical models of a vertically framed and a horizontally framed miter gate. Damage was simulated by reducing the cross-section stiffness over a portion of a major structural member. This was accomplished by reducing Young's Modulus *E* of one frame element in the analysis model (each member is generally composed of several elements). By altering *E*, both the axial and bending stiffness of the element are affected. This might represent the presence of a crack or deterioration of the section. Sensitivity analyses were performed to determine how the magnitude and location of the simulated damage affected the structural response for vertically and horizontally framed miter gates. Several different analyses were performed in which the extent and location of the damage (reduction in *E*) were varied. The damaged elements were located on main structural members (girders, beams, or diaphragms) and were typically about one-tenth the entire member (girder) length. Other deficiencies such as nonlinear support conditions were not considered.

Given measured results of a damaged structure, the selected approach for detecting damaged elements is to modify various structural parameters in the undamaged model using an optimization algorithm (Commander et al. 1992a) to obtain the best comparison between the measured (simulated damage model) and computed strain values. The modifications required to obtain an acceptable comparison are indicative of the existing damage.

The current analysis and optimization procedure is not conducive to purely automated parameter evaluation or damage detection. Some rational approach must be applied to determine which parameters should be optimized (adjustable parameters) in the comparison process. Because parameters that are known accurately should not be altered, it is necessary to identify which parameters are relatively obscure. A typical miter gate model can have several hundred elements, and each element contains up to nine material and cross-sectional variables (i.e., *E*, cross-sectional moment of inertia *I*, cross-sectional area *A*, etc.). A completely indiscriminate optimization of all structural parameters would result in a futile exercise in computer processing. The number of parameters to be optimized cannot exceed the number of independent strain values used in the data comparison (i.e., number of variables cannot exceed the number of equations). In practical terms, the number of independent strain values is limited to the number of monitored locations (locations of strain measurement) that are noticeably affected by the presence of the damage. The

number of independent strain values is also a function of different load cases since strain is affected by a change in the load. With these considerations, a conservative limit on adjustable parameters can be approximated by the number of monitored locations in the vicinity of the damage. Another limiting factor on the number of adjustable parameters is that the number of iterations increases with each variable and computer run time becomes unreasonable.

Another consideration is that optimization cannot be performed on multiple parameters that are strongly correlated or that have identical effects on the structure. For example, the stiffness of a beam is directly dependent on the product of E and I. Only one of the variables can be optimized at a time since the beam stiffness is directly dependent on both terms; infinite combinations of E and I can result in a single beam stiffness.

For this study, it is assumed that damage would most likely be a crack or a deteriorated cross section and that the general area of the damage could be determined by an initial visual or numeric comparison of the measured and computed strain data. To best simulate the effects of this type of damage, E of beam segments in the expected vicinity of the structural damage were selected as the adjustable parameters. These parameters (E of various beam segments) were automatically adjusted within defined limits, and an iterative process of analysis and comparison of results from the simulated damage model with the measured data were performed. E_{abs} was used as the measure of improvement (objective function) for successive iterations during the optimization process. During the optimization procedure, iteration was stopped when one of the following conditions was met: (a) the objective function reached an acceptable value, (b) the objective function could not be improved over a specified number of iterations, or (c) the values of the adjustable parameters exceeded the user-defined limits.

In the current state of the optimization process, selection of adjustable parameters must be made on some rational basis. Typically, irregular response characteristics can be determined by comparing calculated and measured strain as a function of loading. Based on the comparison, reasons for the irregular behavior can be proposed. Optimization of appropriate variables then verifies or contradicts the proposed assumption. The drawback to this process is that it relies heavily on engineering experience and intuition. Care must be taken to ensure that sufficient strain data are available to ensure that a unique solution exists between the adjustable parameters. It is recommended that the number of available independent strain values be equal to or exceed the number of adjustable variables.

Damage Detection on Vertically Framed Miter Gate

In order to develop a method for damage detection, an initial task is to determine if and how various types and degrees of damage affect the strain readings at selected gage locations. A damage sensitivity analysis was performed by examining the effect on strains as the degree of damage at a single location was varied and as the location of damage varied with respect to the gage locations. For each damage position, an analysis was conducted for four different degrees of applied damage. Damage was simulated simply by reducing E of the elements representing the damaged areas. E_d was assigned values of $0.5E$, $0.1E$, $0.01E$, and $0.001E$, where E_d is Young's modulus of the damaged element.

Damage detection with 32 monitored locations

A two-dimensional finite element grid model identical with that developed for the analysis of the Emsworth miter gate (Commander et al. 1992c) was used for the simulated damage and analytical models for vertically framed miter gates. For practical considerations, 32 gage locations of an actual field test (Commander et al. 1992c) were considered initially. At each of the selected member cross sections, strain was measured (or calculated) on the upstream and downstream flange, in order that axial force and flexural bending could be determined. An elevation view of the miter gate leaf with the gage locations is shown in Figure 1, and a drawing of the finite element mesh representing the gate leaf is shown in Figure 2.

Simulated damage on member without strain gages. The first simulated damage trial was a reduction in E for one element at approximately the midlength of vertical beam No. 4 (VB4) (see Figure 1). VB4 does not include any gage locations; however, strains were monitored (simulated damage model) and computed at locations on the adjacent vertical beams, VB3 and VB5. Strain data were computed for the simulated damage model and were used as the baseline measured data. An analysis of the structure was then conducted assuming that the existence of damage was unknown (undamaged analytical model). Results produced by the undamaged analytical model were compared with those of the simulated damage model (measured) to determine if the damage were detectable based on the comparison. The degree of influence of the damage was based on visual comparison of the measured and calculated strain history graphs and numerical error quantities for individual gage locations and the overall response. After the sensitivity analysis was completed, efforts were directed towards applying a systematic process to locating and quantifying the extent of damage.

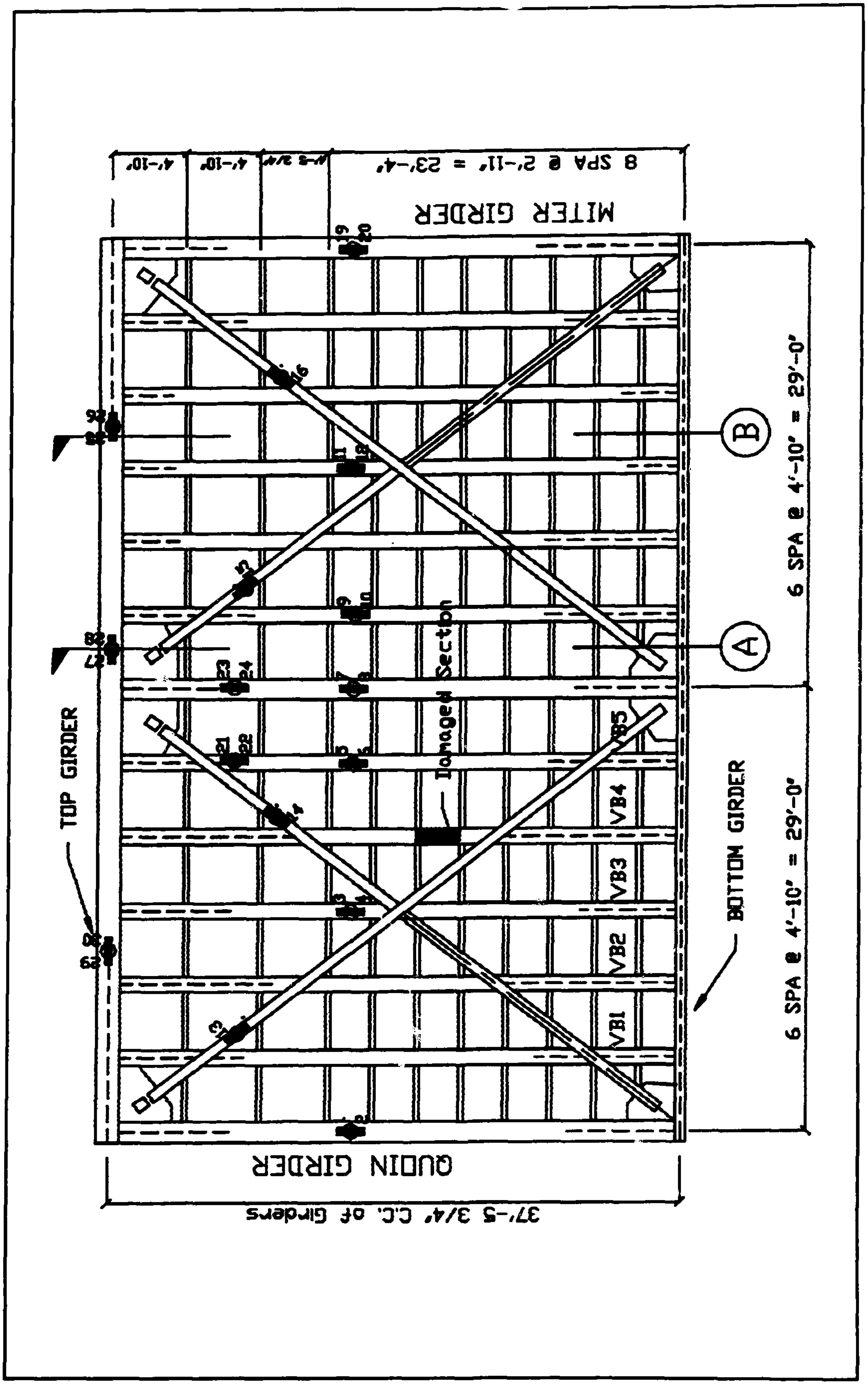

Figure 1. Vertically framed miter gate (Emsworth), 32 monitored locations

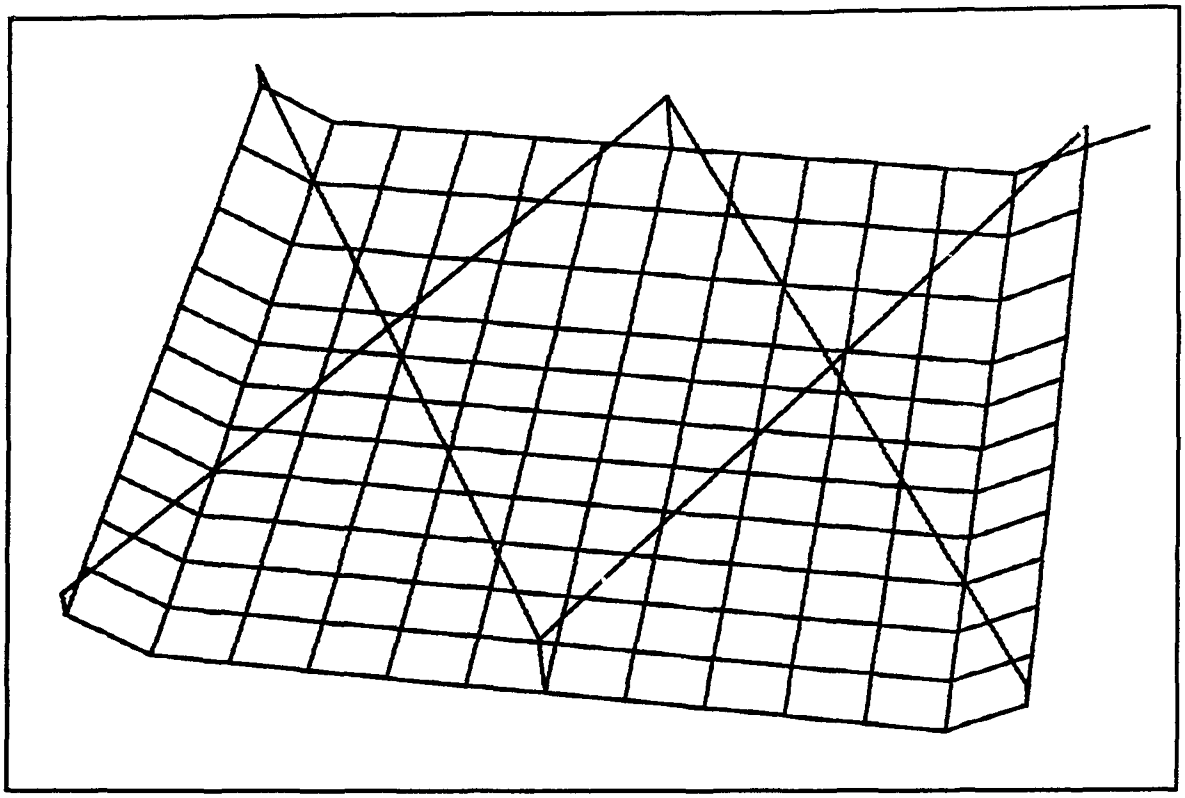

Figure 2. Emsworth miter gate finite element mesh

After the first series of analysis comparisons, it was apparent that the type of damage assessment desired in this study was not possible with the given number of monitored locations. Since there was no instrumentation on the damaged beam, only secondary effects due to the change in load transfer could be monitored. The only noticeable effect on the behavior was a slight increase in strain on the adjacent beams, VB3 and VB5. Even with the segment on VB4 damaged to the fullest extent ($E_d = 0.001E$), the overall data correlation between the simulated damage and undamaged models was better than one could expect for an actual experiment. Information from the strain data was insufficient to locate or quantify the simulated damage. The number of gage locations was very low compared with the number of elements that could possibly be damaged, and a unique solution to reproduce the simulated damage model strain data does not exist. Multiple variations of the original undamaged model could reasonably reproduce the strains from the damaged model. For example, the stiffness anywhere along VB4 could be reduced to an appropriate amount so that the adjacent beams, VB3 and VB5, would carry more of the load and thus increase the flexural response in the elements that had the higher strain readings.

Simulated damage on member with strain gages. The effect of damage location relative to the instrumentation was examined for the case of damage simulated on VB5. Analyses were again conducted with the simulated damaged model for E_d of $0.5E$, $0.1E$, $0.01E$, and $0.001E$. In this case, the simulated damage was much more apparent, particularly with the

higher degree of deterioration (lower E_d). Since the gage locations were closer to the damaged section, the effects on the strain comparisons were more significant than those for the case of damage on VB4. With E_d equal to $0.5E$, the strain at the location of the VB5 gages was reduced compared with the case of E_d equal to E due to increased flexibility at the damaged segment. As E_d was reduced to $0.001E$, the sign (direction) of the flexural bending reversed at the VB5 gage locations. The reversal of bending showed that the ends of VB5 behave as cantilever beams effectively joined by a hinge at the damaged section of the beam. The magnitude of strains on the vertical girders adjacent to the damaged girder increased with larger reductions in E because they had to carry more load as the damage was increased. (Since no locations were monitored on VB4, it could not be observed through any type of data comparison.)

Based on the initial sensitivity analysis, it was concluded that damage can be detected if there are enough gage locations in the vicinity of the damage and if the damage is sufficient to cause some change in the load transfer characteristics of the structure. It is also apparent that with sufficient gage locations, damage detection may be facilitated by searching for a specific pattern in the response comparisons. Typically, the strains on the beam with the damaged section will be reduced and the direction of the flexure may change from the undamaged condition. Additionally, the strains on the adjacent members will increase in magnitude. In order to observe such a pattern, it is necessary to instrument every major structural member (girder, beam, diaphragm, and diagonal) at least at one location. Additional gage locations along the length of a beam or girder provide information for the member along its length and can help determine the end restraint conditions.

Damage detection with 64 monitored locations

Additional gage locations were chosen for the model, as shown in Figure 3, to obtain a total of 64 gage locations. All of the vertical members were monitored at two separate cross sections along the lengths (just above the lower pool level, which is approximately at midspan and at approximately the upper quarterpoint).

With the additional 32 locations, the effect that the damage would have on comparison of damaged and undamaged model strain data (locally and overall) could be examined further. The damaged beam segment was again located on VB4, and a sensitivity analysis was performed. As before, the analysis was run with four different levels of simulated damage (for the damaged segment $E_d = 0.5E$, $0.1E$, $0.01E$, and $0.001E$). The influence of the damage was examined on a global basis (consideration of all monitored locations) and locally for three locations near the altered section. The numerical quantities E_{abs}, E_{ave}, E_{per}, and CF were calculated for comparison purposes. Table 1 shows the overall effect of the damaged section due to the four different levels of damage. The overall E_{per}, was minimally affected by the damaged section. The E_{abs} is a large number;

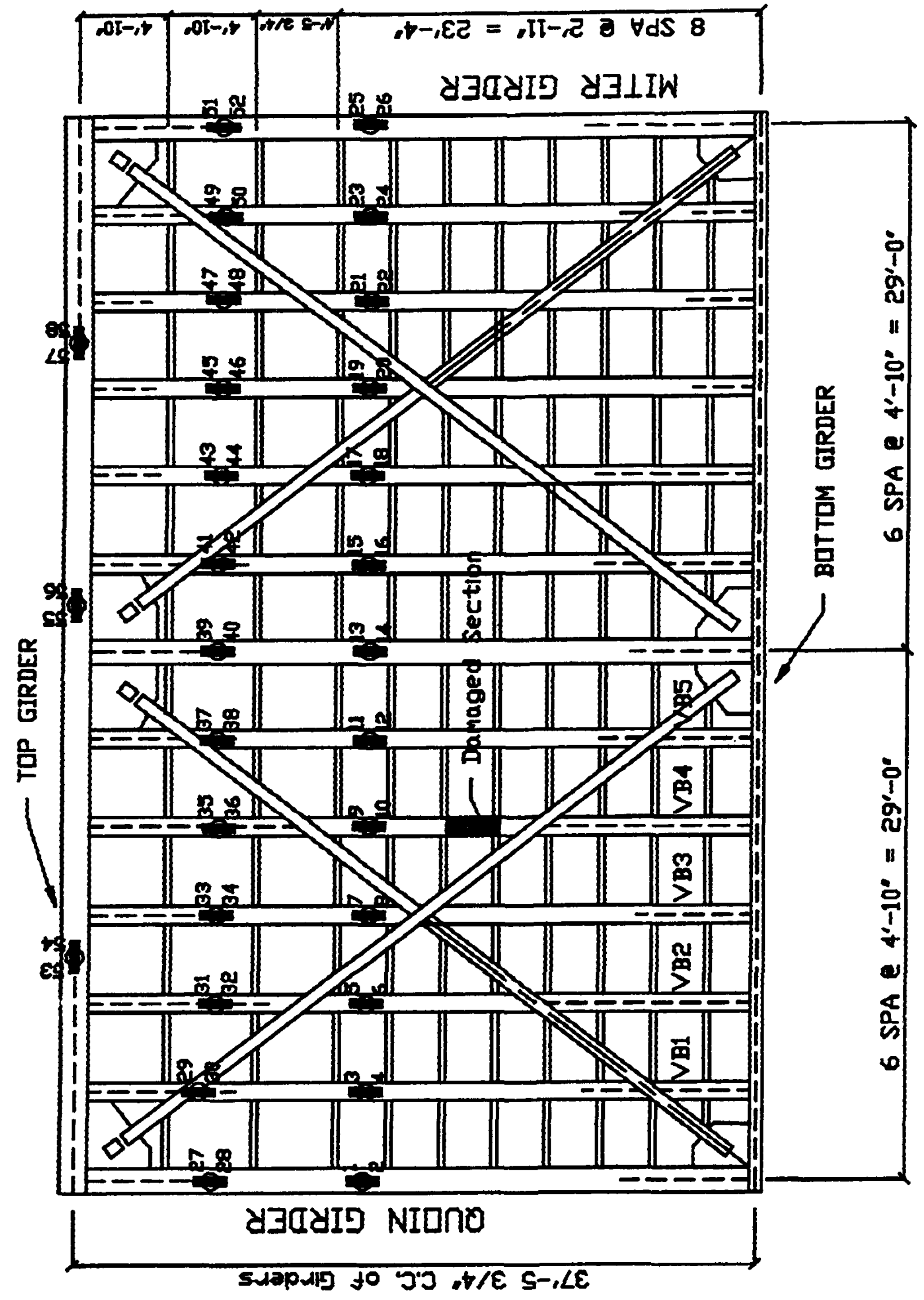

Figure 3. Vertically framed miter gate (Emsworth), 64 monitored locations

however, this includes the summation of all the absolute strain differences for 64 monitored locations and 12 different head differential levels. In this case, E_{ave} and *CF* provide a better conceptual measure of the comparison. The small effect on the overall response is due mainly to the large number of monitored locations away from the vicinity of the damage. The total number of strain readings that are not affected by the damage outweighs the number that are. Therefore, it was again concluded that individual gage errors should be examined when searching for structural damage.

Table 1
Overall Effect of Damaged Section (12 Load Cases and 64 Gage Locations)

E_d	E_{abs}	E_{avg}	E_{per}	*CF*
0.5*E*	380	0.5	0.0	0.9999
0.1*E*	2422	3.6	1.2	0.9940
0.01*E*	7906	10.3	13.1	0.9385
0.001*E*	9648	12.6	19.8	0.9110

Figures 4 - 6 illustrate how the strain comparisons change with the degree of damage. Strain records for the simulated damage and analytical conditions are shown for locations 8, 10, and 36. The three plots correspond to the three greatest degrees of damage ($E_d = 0.1E$, $0.01E$, and $0.1E$). Tables 2 - 4 show the results for the local effects for locations 8, 10, and 36, respectively (see Figure 3). The individual gage results are presented in terms of total error E_t, E_{per}, and *CF*. E_t is the summation of the strain differences for an individual gage location from all of the applied load cases. It is different from the E_{abs} in that the sign of the error indicates whether the theoretical strains are greater or less than the measured strains. A positive total error indicates that the predicted (undamaged model) strains are greater than the measured (simulated damage model) strains. E_{per} and *CF* are computed in the same manner as for the overall responses. The *CF* for an individual location is generally not useful unless the damage causes a reversal in strains. Generally, the individual correlation coefficients indicate a favorable relationship between the measured and analytical data ($CF \approx 1.0$) even when a large difference in strain magnitude exists. However, as shown by the results for locations 10 and 36, a change in sign or a change in shape of the strain history is immediately detected by a change in the correlation factor. Visual examination of the strain records and the numerical error comparisons provide an indication that some type of damage is present on VB4. This is particularly true for the cases simulating more severe damage because the direction of flexure changes on VB4. The change in sign of the flexural bending is easily identified by the negative correlation factors.

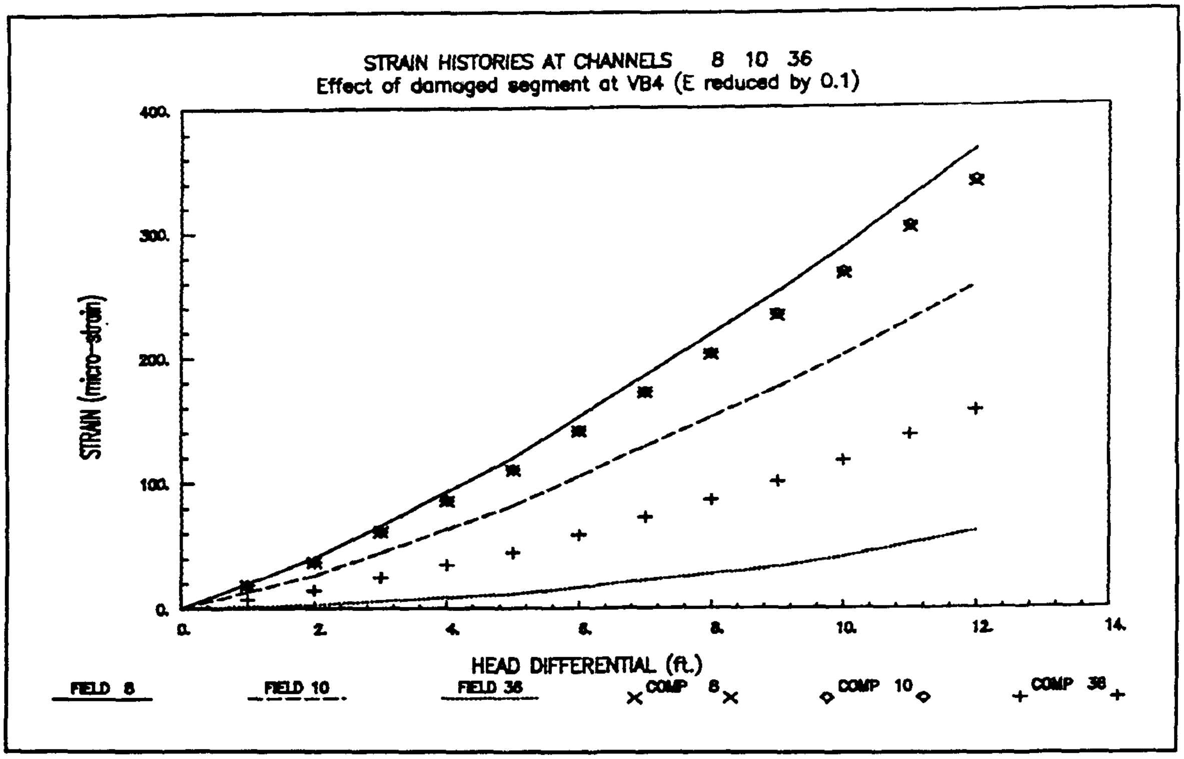

Figure 4. Simulated damage and undamaged model strain comparison for locations 8, 10, and 36 (E_d = 0.1)

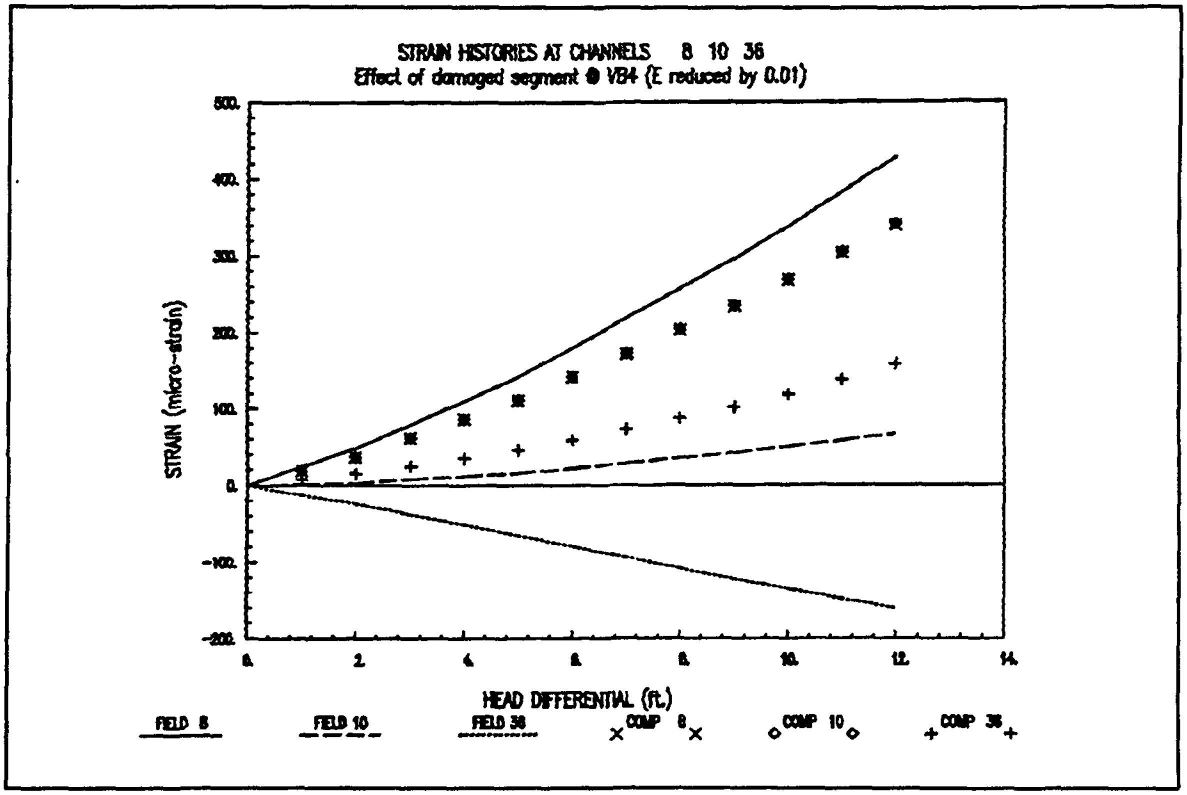

Figure 5. Simulated damage and undamaged model strain comparison for locations 8, 10, and 36 (E_d = 0.01)

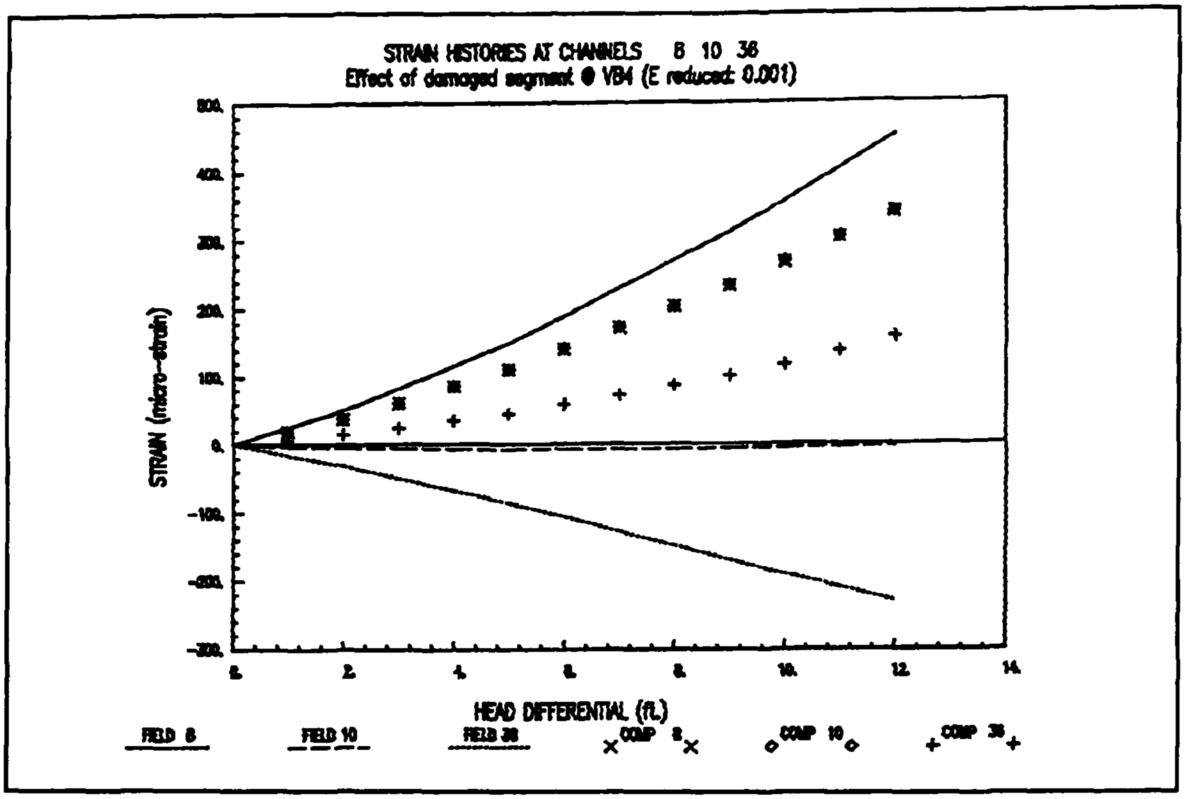

Figure 6. Simulated damage and undamaged model strain comparison for locations 8, 10, and 36 (E_d - 0.001)

Table 2 **Local Effect of Damage at Location 8 (12 load cases)**			
E_d	E_t All Load Cases	E_d	CF
0.5E	3.9	0.6	1.0
0.1E	26.7	3.9	1.0
0.01E	88.5	13.0	1.0
0.001E	112.0	16.4	1.0

Table 3 **Local Effect of Damage at Location 10 (12 Load Cases)**			
E_d	E_t All Load Cases	E_{per}	CF
0.5E	-12.4	-1.8	1.0
0.1E	-83.8	-12.2	1.0
0.01E	-275.6	-40.2	0.997
0.001E	-344.1	-50.0	0.171

Table 4
Local Effect of Damage at Location 36 (12 Load Cases)

E_d	E_t All Load Cases	E_{per}	*CF*
0.5*E*	-13.6	-4.3	1.0
0.1*E*	-96.0	-30.3	0.994
0.01*E*	-318.2	-100.0	-0.990
0.001*E*	-387.6	-120.9	-0.994

Damage evaluation

Since it was apparent that under many circumstances the presence of damage could be detected, the next goal was an attempt to evaluate the damage. The analysis was conducted with the damaged element on VB4, and strains were calculated for the 64 gage locations. Damage was simulated as a nearly complete fracture with $E_d = 0.001E$ on the sixth beam segment (see Figure 3). By means of measured (simulated damage model) and calculated (undamaged analytical model) strain comparisons, an attempt was made to locate and evaluate the damage through parameter optimization. For the parameter optimization of the analytical model, it was assumed that it was known that the damage was located somewhere on VB4 based on the visual and numerical strain comparisons. *E* for the 11 beam segments on VB4 were selected as the unknown parameters with upper and lower limits of 29,000 and 0.0 ksi.

With the appropriate parameters set, the optimization analysis on the undamaged analytical model was performed. After approximately 200 analysis and comparison iterations, the program terminated with a nearly perfect correlation between the *computed* and *measured* data. The computer run time required to perform the entire optimization was less than 2 hr on a 486 (50 mHz) personal computer. After the optimization process was complete, the optimized values for *E* were compared with the original values assigned for the simulated damage model (see Table 5). Through the optimization, E_{per} was reduced to less than 0.1 percent, and the optimized values of *E* are far from equal to those defined for the simulated damaged model. Therefore, it is apparent that the chosen gage locations were not sufficient to obtain a unique solution for the given damage situation.

Table 5
***E* for the Simulated Damage and Optimized Analytical Models (Vertically Framed)**

Beam Segment Number	E (ksi)		
	Simulated Damage Model	Undamaged Analytical Model	
		Initial	Optimized
1	29,000	29,000	24,439
2	29,000	29,000	29,000
3	29,000	29,000	25,839
4	29,000	29,000	29,000
5	29,000	29,000	13,182
6	30	29,000	999
7	29,000	29,000	949
8	29,000	29,000	768
9	29,000	29,000	8
10	29,000	29,000	8
11	29,000	29,000	8

Even though the optimized parameters do not converge to those of the simulated damage model, the results do provide an indication of the damage location. The simulated damage represents a nearly complete fracture at segment 6 on VB4. The optimized results indicate that the beam elements above segment 6 (segments 1 through 5) remained relatively stiff (the optimized values for *E* are near the actual *E* value of 29,000 ksi). An abrupt change (decrease) in *E* (stiffness) occurred between segments 5 and 6, and the elements below segment 6 obtained *E* approaching zero. The large decrease in stiffness between segments 5 and 6 indicates that segment 6 is likely damaged. The low values for *E* on the lower beam segments show that they have little effect on the compared strain readings. Since all of the monitored locations are above the location of the damage and the damage essentially simulates a complete fracture situation, the computed results yield a reasonable assessment. Through careful examination of the optimization results, damage can be located even when it is concluded that a unique solution does not exist.

The ability to isolate damaged sections could be improved with more monitored locations including positions underwater. However, reasonable judgment must be exercised in selecting data requirements because an excessive number of monitored locations can make field testing impractical.

Although the optimization process successfully minimized the error between *measured* and *computed* data, the solution was not entirely conclusive. Examination of the results was supplemented with engineering judgment to predict the location of the damage. To verify the location and more completely evaluate the extent of the damage, it was assumed that the location of the damage was correctly identified so that the number of unknown quantities was limited to a single adjustable parameter (E of the damaged segment). The optimization process was then performed to determine if the single unknown parameter could be correctly evaluated. In this analysis, E_{per} was again reduced to an acceptable level (0.1 percent), and the simulated damage was correctly evaluated. The optimized value for E was within 10 percent of the value applied to the simulated damaged model.

Conclusions

In this case study, a procedure was outlined for application of the integrated approach to damage detection and structural assessment. The optimization algorithm, in its current state, is a useful tool for locating and evaluating damage but cannot be used as an automated procedure for structural evaluation. Engineering judgment and experience are still required to interpret the response comparisons and determine what structural parameters should be optimized. Engineering experience is also required to interpret the results when the optimizer is used. However, the optimizer does provide a source of verification for assumptions made by an engineer.

It was determined that the number of gage locations typically used to monitor general response behavior may not be sufficient to perform a complete structural evaluation. When damage detection is desired, it is necessary to instrument every major structural element in at least at one location. With miter gates, instrumentation typically consists of two gages or transducers on a single beam or girder cross section so that bending and axial responses can be measured.

Damage Detection on Horizontally Framed Miter Gate

Damage detection

Damage detection exercises similar to those performed for the vertically framed Emsworth miter gate were performed for a horizontally framed miter gate. The lower horizontally framed miter gate at the John Hollis Locks and Dam was used as a prototype. Based on the conclusions for the vertically framed miter gate case study, gage locations were selected so that most of the major structural members above lower pool were instrumented. Locations at multiple cross sections along the length

of each girder were monitored to obtain information concerning the longitudinal variation in behavior. Selected locations were at symmetric positions along each girder so that symmetry of the responses could be checked. Three cross sections were monitored on each horizontal girder (midspan and approximately the one-quarter points on each end of the girder). Figure 7 is a diagram showing the elevation layout of the lock gate leaf with the monitored locations. For practical purposes, a maximum of 64 locations were monitored.

As done previously, various degrees of reduction in E were applied to elements representing a damaged location ($E_d = 0.5E$, $0.1E$, $0.01E$, and $0.001E$). Damage was simulated on girder G10 on the fifth segment from the quoin end (see Figure 7). Strains on girder G10 and both of the adjacent girders were monitored. As with the previous study, the responses from the simulated damaged model are considered to be measured strains.

In Tables 6 - 10, numerical results of the data comparisons between the simulated damage model and the analytical model are presented for the overall response (all monitored locations) and for four individual gage locations. Results from locations 10, 14, 15, and 22 (see Figure 7) are presented since they were most affected by the simulated damage. As expected, the global effect (see Table 6) of the damage is minimal because a large number of monitored locations are not in the vicinity of the damage. However, analytical and *measured* strain histories for locations nearest the damaged segment did indicate a significant difference. In particular, the change in flexural curvature (difference in strain between the upstream and downstream flange gages) provides the greatest indication of irregular behavior.

Table 6
Global Effect of Damaged Section (7 Load Cases and 64 Gages)

E_d	E_{abs} (micro-strain)	E_{ave}	E_{per}	*CF*
$0.5E$	922	2.1	0.1	0.999
$0.1E$	2167	4.8	0.4	0.998
$0.01E$	2594	5.8	0.5	0.997
$0.001E$	2642	5.9	0.5	0.997

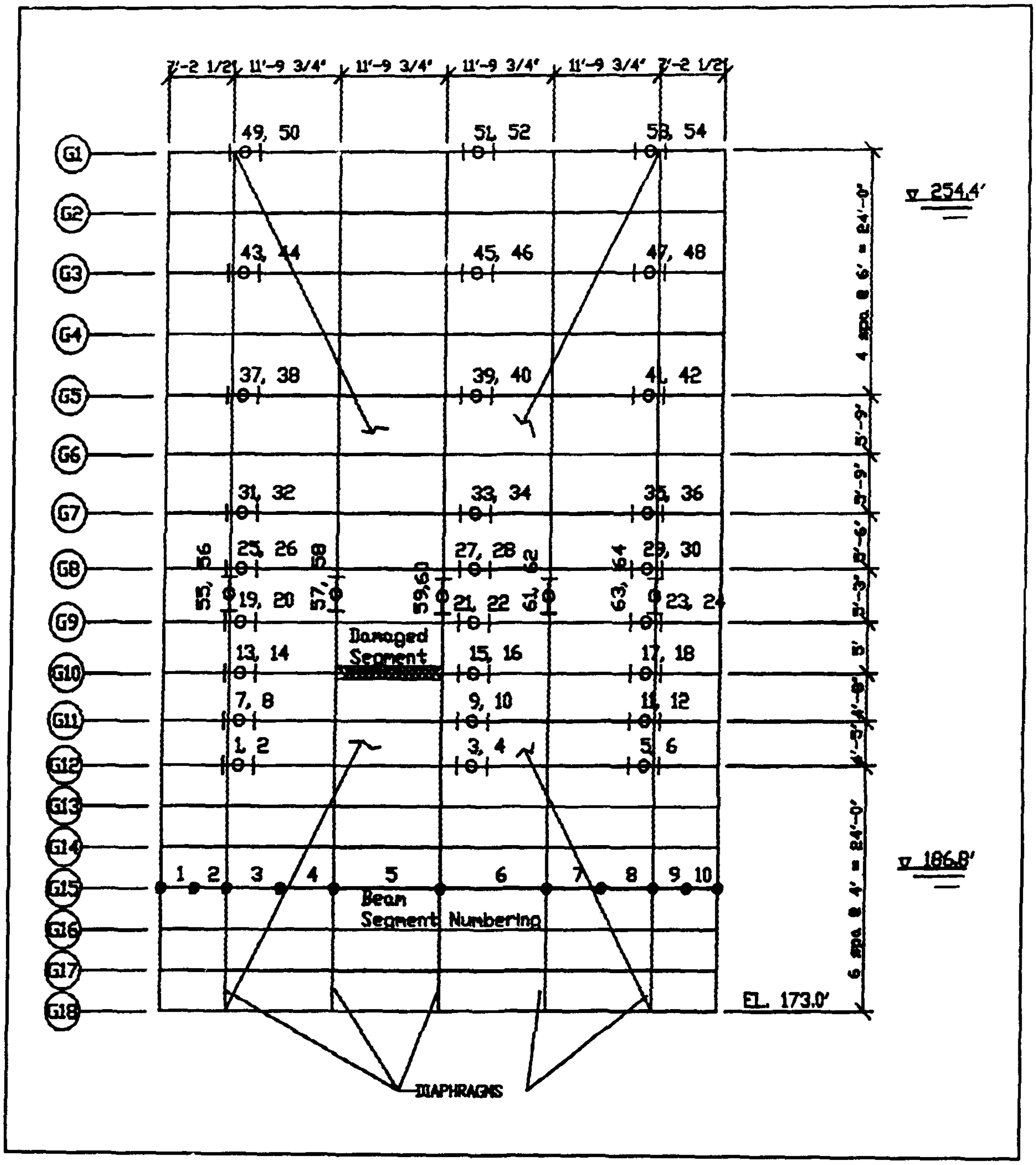

Figure 7. Horizontally framed miter gate (Bankhead) with 64 monitored locations

Table 7
Local Effect of Damage at Location 10 (7 Load Cases)

E_d	E_t (micro-strain)	E_{per}	*CF*
0.5*E*	6.9	5.4	1.0
0.1*E*	18.6	14.1	1.0
0.01*E*	24.1	18.1	0.999
0.001*E*	24.8	18.6	0.999

Table 8
Local Effect of Damage at Location 14 (7 load cases)

E_d	E_t (micro-strain)	E_{per}	*CF*
0.5*E*	39.7	2.4	1.0
0.1*E*	88.6	5.3	1.0
0.01*E*	103.1	6.2	1.0
0.001*E*	104.7	6.2	1.0

Table 9
Local Effect of Damage at Location 15 (7 Load Cases)

E_d	E_t (micro-strain)	E_{per}	*CF*
0.5*E*	43.6	3.3	1.0
0.1*E*	98.0	7.4	1.0
0.01*E*	116.0	8.7	1.0
0.001*E*	118.0	8.9	1.0

Table 10
Local Effect of Damage at Location 22 (7 load cases)

E_d	E_t (micro-strain)	E_{per}	*CF*
0.5*E*	10.5	11.6	0.999
0.1*E*	27.7	31.4	0.958
0.01*E*	35.3	40.2	0.138
0.001*E*	36.3	41.2	-0.146

Based on a numerical and graphical inspection of the response comparisons, it can be assumed that the general location of the damage is near the left side of girder G10. In particular, items providing the best clues for locating the damage are the largest magnitude and percent errors from individual monitored locations, a symmetry check in the responses and response comparisons on each girder, and a search for the typical response pattern associated with damage (lower than predicted strains on the damaged girder coincident with larger strains on adjacent girders). Figures 8 - 10 illustrate how the flexural responses are affected in the vicinity of the damaged segment. Simulated damage model results show that girders G9 (Figure 8) and G11 (Figure 10), located just above and below the damage, experience larger than predicted flexure at midspan. Girder G10 (Figure 9), which contains the damaged segment, has less than predicted flexure at midspan. In Figures 8 - 10, the continuous lines represent the simulated damage model ("field") results, and the discrete points are the predicted values ("comp").

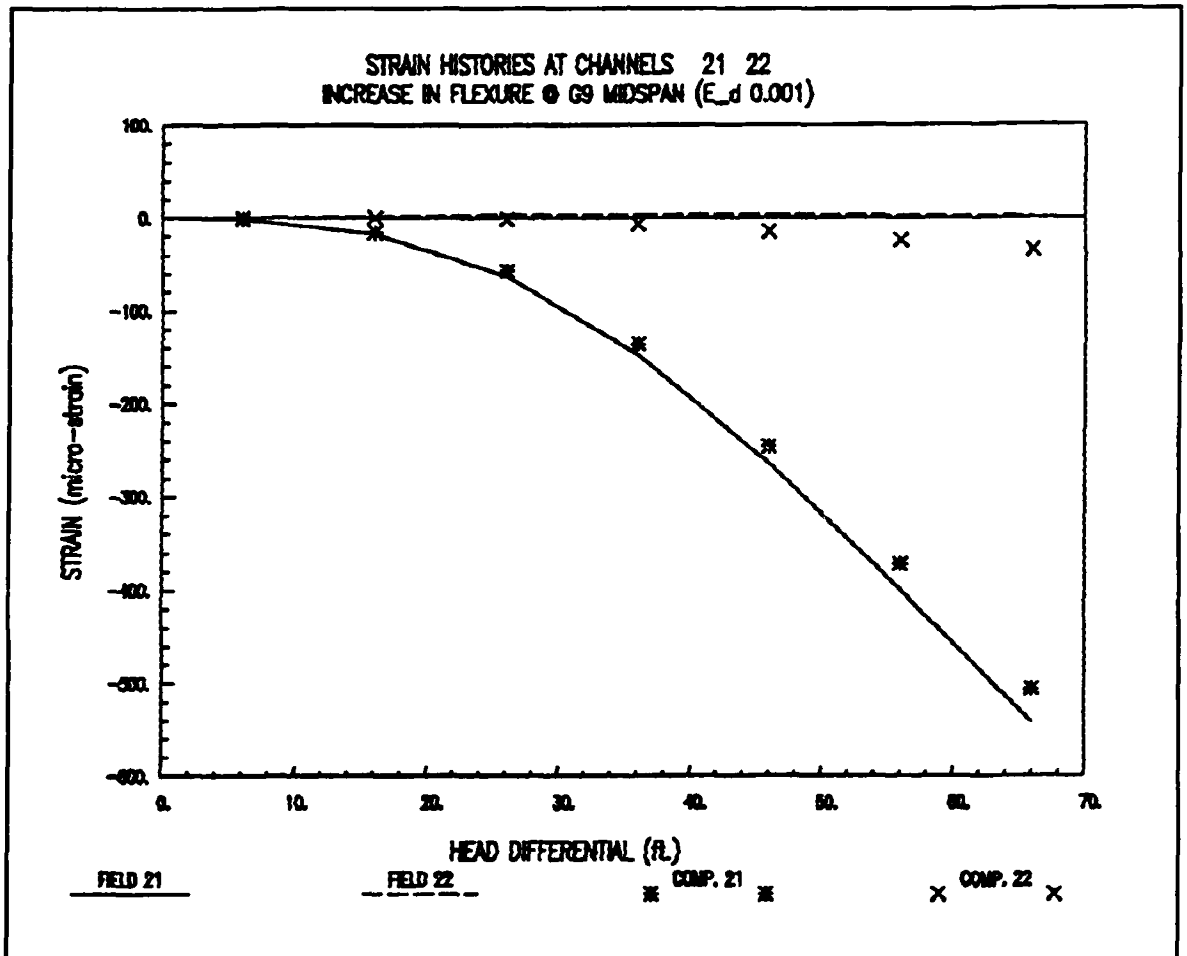

Figure 8. Simulated damage and undamaged model strain comparison for midspan of G9

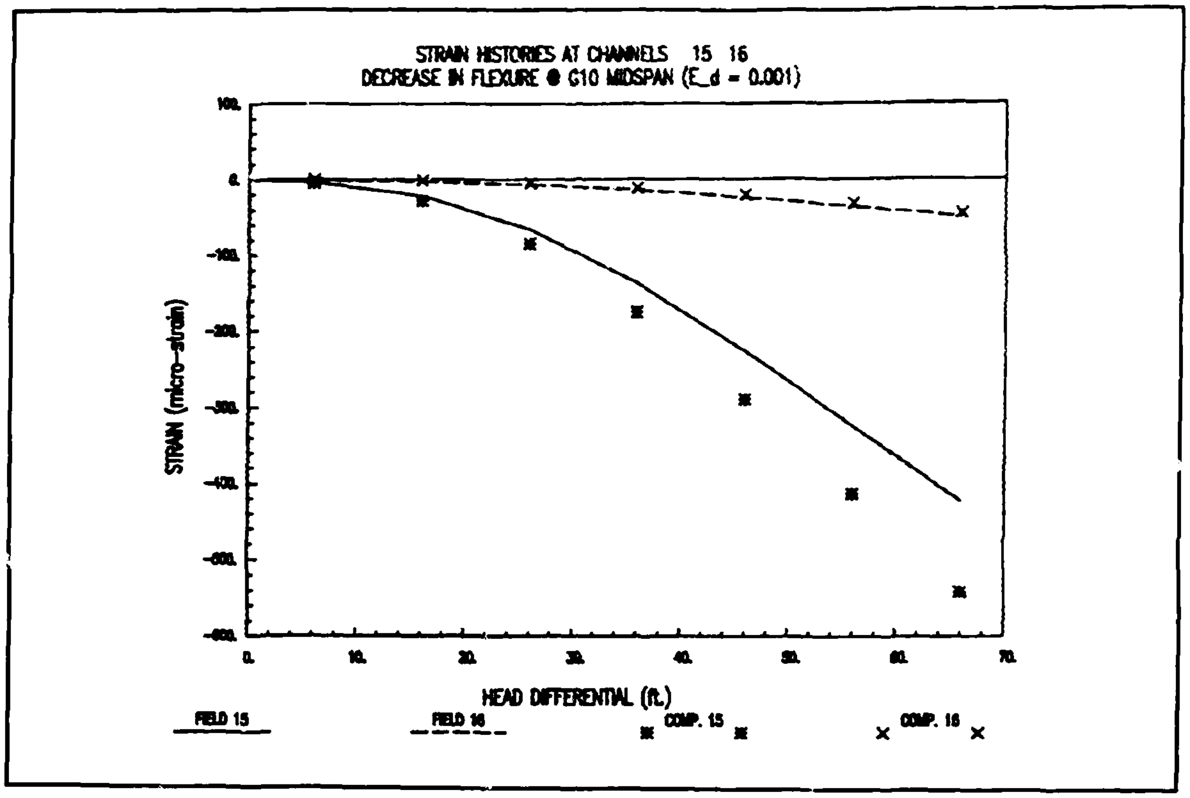

Figure 9. Simulated damage and undamaged model strain comparison for midspan of G10

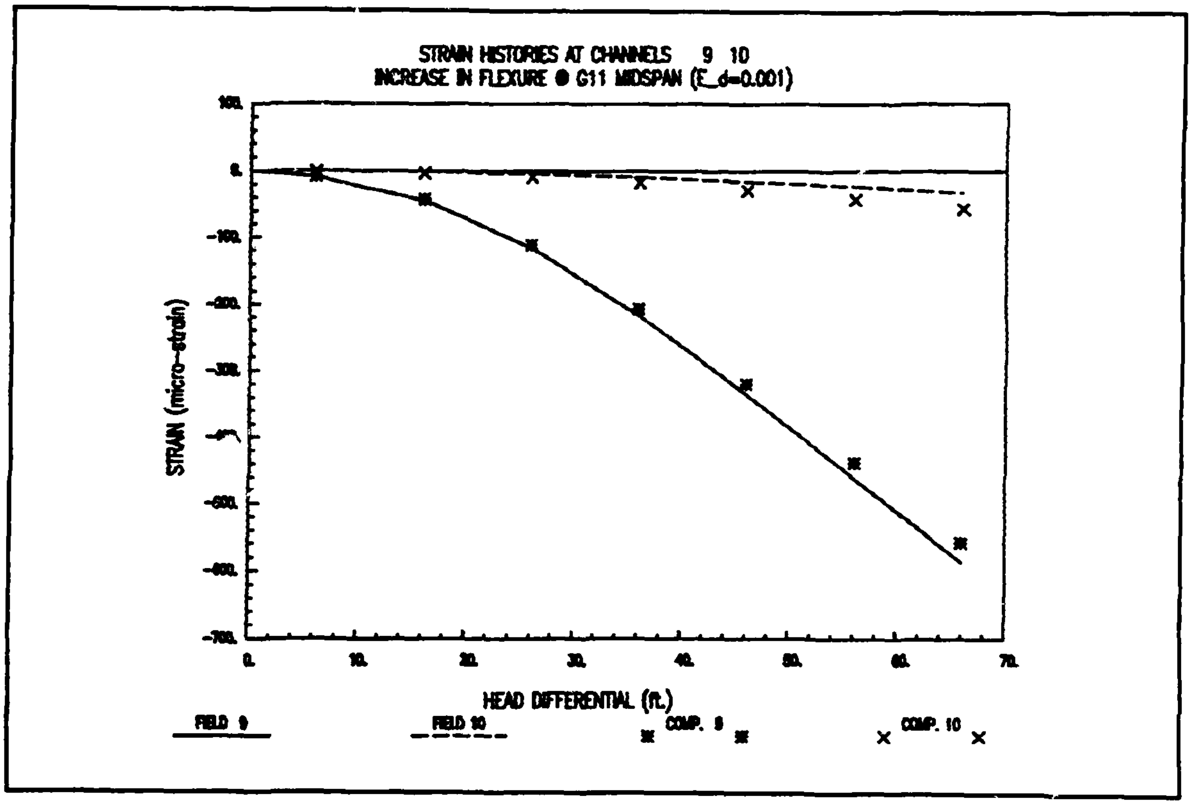

Figure 10. Simulated damage and undamaged model strain comparison for midspan of G11

Damage evaluation

With the general location of the damage known, an attempt was made to identify the damage using the optimization process. E for five beam segments on the left half of G10 were defined to be variable, and the optimization process was then executed with the undamaged analytical model. With E_d of the damaged segment equal to $0.001E$, the *measured* strains from the simulated damaged model were used as the comparison basis.

In this case, the optimization was successful becaus: there were several gage locations (approximately 10 to 12) in the vicinity of the damaged section and only five parameters were defined as variable. The error level was reduced to well within acceptable limits (E_{per} was below 0.05 percent), and the resulting E were close to those used to simulate the damage. The optimization process correctly identified the segment containing the reduced modulus. Table 11 provides the optimization results including the original and optimized values of the adjustable parameters.

Table 11
***E* for the Simulated Damage and Optimized Analytical Models (Horizontally Framed)**

Beam Segment Number	*E* (ksi)		
	Simulated Damage Model	Undamaged Analytical Model	
		Initial	Optimized
3	29,000	29,000	31,490
4	29,000	29,000	26.350
5	30	29,000	250
6	29,000	29,000	30,322
7	29,000	29,000	29,850

Based on the strain comparisons obtained from this case study, it is apparent that damage on submerged girders would be difficult to detect since the monitored locations were located only above the lower pool elevation. Even when the damaged segment approached a complete fracture situation, strains obtained from girders not directly adjacent to the damaged segment were affected minimally. The response changes at locations two girders away were so slight that the comparison between the *measured* and *computed* strain were typically better than could be expected from an actual field test.

4 General Conclusions

Through the case studies presented in Chapter 2 and cases of simulated damage presented in Chapter 3, a systematic approach was developed and used to detect and quantify the effects of structural damage. Visual and numerical comparisons of measured (or simulated damage model) and calculated strain responses were used to detect the presence of damage and its general location. Assumptions based on the visual inspections were then verified or refuted by using an optimization process to reproduce the effect of the damage.

This damage assessment process is far from being automated because considerable engineering judgment and experience are required to interpret and evaluate the results. Furthermore, in the simulated damage studies, only localized damage (i.e., a crack) was modeled by decreasing E of a small beam segment. Other types of damage may have different effects on the structural responses, and the process of identifying various other types of damage may vary. However, a sound basis for data comparison and damage detection has been defined.

Throughout this study, the function and limitations of the optimization process were identified. Following is a list of conditions that were most apparent and must be considered when performing optimization.

a. The optimization process is most effective in quantifying parameters that are known to be obscure. Damage can be quantified in cases where the damaged section has been located by visual inspection or when the deterioration can be considered constant over a large region (i.e., reduced cross section for an entire beam or group of beams). The advantage of working with groups of elements is that the number of parameters to be optimized is reduced significantly, and it is much more likely that a unique solution can be obtained.

b. The ability to detect and quantify damage is directly dependent on the number of locations that are monitored in the damaged region. For this reason, at least one cross section of every major structural element should be instrumented. When possible, two or three cross sections should be instrumented along the length of a member so that the flexure along the element can be adequately defined.

c. The ability to detect damage is dependent on the its magnitude. The measurable effect on the strain readings increases with the magnitude of the damage and the overall effect on the load path.

d. To detect damage, the main criteron is that the damage must have some significant effect on the load transfer characteristics of the structure. Different types of damage may affect the ability to detect the damage. A section that has been buckled due to a barge impact will likely have a much different effect than a section with a cracked flange plate. Changes in boundary conditions provide the most obvious indications of damage since the load path of the entire structure is altered.

e. Localized damage can be detected if it is of sufficient magnitude; however, determining the exact location of the damage through optimization may not be possible. The number of unknown quantities in the numerical model must be minimized so that a unique solution exists.

f. Currently, the most useful tool for detecting the presence of damage is the manual evaluation of graphical and numerical comparisons of measured and calculated strain. This process might be automated by computer programs that analyze the measured and calculated data while searching for trends that might indicate various types of damage. For example, the structural geometry, boundary conditions, and loading of miter gate leafs are typically symmetrical. Nonsymmetrical responses would indicate a probable deficiency.

g. If the comparisons of measured and computed strains are to have any significance, the analytical model must be an accurate representation. The structural geometry, member properties, boundary conditions, and applied loads must all be basically correct if structural damage is to be detected. Detecting the presence of damage or obscure boundary conditions is based on the differences in measured and calculated strain data. It must be assumed that if no damage or irregularities exist, a nearly perfect strain comparison would be obtained.

The integrated field testing and analysis correlation system has proven valuable in both damage detection and damage assessment. Various types of damage have been detected directly from measured strains and further verified by comparing the strains with computed values. When structural damage is identified, either from test data or by other means, the cause and/or effect of the damage can usually be explained with the aid of analytical procedures.

The ability of the integrated system to detect damage depends primarily on the type and magnitude of the existing damage. Cases in which miter gate boundary conditions are altered from what is expected

generally cause a significant change in the load transfer characteristics of the structure and thus have a great effect on the strain responses. These types of irregularities can generally be detected by evaluation of measured strains or comparison of the measured and calculated strains. However, based on the simulated damage exercise, it is apparent that the system has limited capabilities in detecting localized damage such as cracks. The effect on load transfer characteristics due to a damaged section is usually very localized. The load transfer characteristics seem to be only slightly affected when moderate damage is applied to major structural members. Unless several locations are monitored in the immediate vicinity of the crack, effects of the reduced member cross sections can be considered measurable only after the section is significantly diminished. It is likely that damage of this proportion would be visible long before the effects on strain responses would be sufficient for the integrated system to detect the damage. For this reason, field testing and analysis correlations cannot be considered a substitute for visual inspection but should be viewed as a tool to complement visual inspection.

Based on the simulated damage studies, large reductions in E can generally be detected through data comparison if sufficient numbers of locations are examined. This is beneficial for cases in which the damaged section is not visible because it is underwater. This is especially true for vertically framed miter gates in which all of the major structural members can easily be accessed for instrumentation. The limitation to the process, though, is that determining the exact location of the damage is generally not possible because quite often multiple degrees of deterioration along with various locations of damaged sections can produce identical effects on the strain readings.

Currently, the optimization software is not sophisticated enough to perform damage detection on an automated basis. The selection of adjustable parameters must be done with some type of rational approach. The current approach to detecting the presence of damage is to examine strain data graphically and evaluate numerical data comparisons to determine locations that exhibit poor data correlations. Determining the cause of the discrepancies between the measured and computed data is based on engineering experience and the intuition of the engineer. Future generations of the integrated analysis and correlation system should include procedures that automatically detect irregular responses (poor correlations between the measured and computed strains) and determine which structural parameters have the greatest effect on the questionable responses. Once a sound set of rules for detecting damage is developed, data search routines can be incorporated to provide a more automated program.

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13. ABSTRACT *(Maximum 200 words)*

A primary goal of the Evaluation and Repair of Hydraulic Steel Structures work unit is to develop structural evaluation tools that can be used to assess the current condition of aging steel lock gates. In this study, an integrated experimental and analytical system is evaluated to determine if such a system could be used in identifying existing structural damage on the basis of comparing measured and calculated strain data without having information from prior detailed structural inspections.

The integrated system proved to be valuable in both damage detection and assessment. Various types of damage were detected directly from measured strains and further verified by comparing the strains with computed values. When structural damage was identified, either from test data or by other means, the cause and/or effect of the damage could usually be explained with the aid of analytical procedures. However, at this time, the assessment process cannot be fully automated because considerable engineering judgment and experience are required to interpret and evaluate the results.

14. SUBJECT TERMS

Emsworth Lock and Dam	Miter gates
Evaluation system	Numerical modeling
Mississippi River Locks and Dam No. 26	Red River Lock and Dam No. 1
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